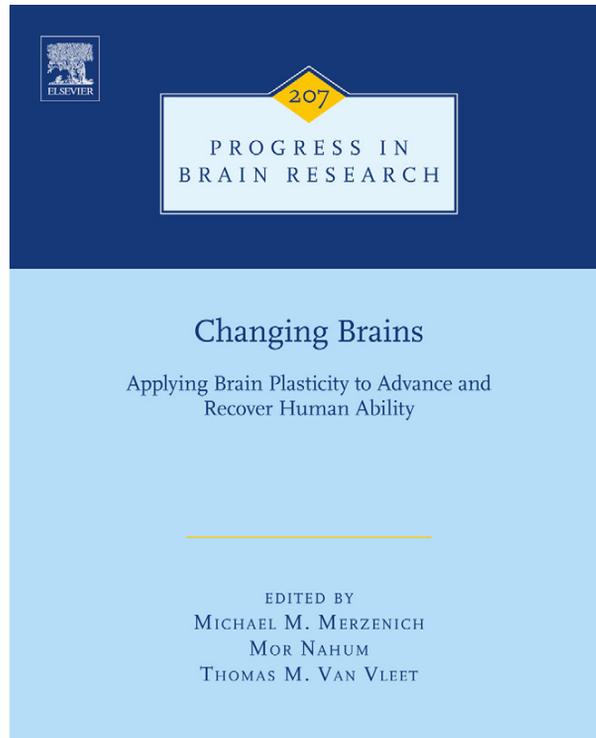


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Music Training for the Development of Reading Skills

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Abstract

The beneficial effects of musical training are not limited to enhancement of musical skills, but extend to language skills. Here, we review evidence that musical training can enhance reading ability. First, we discuss five subskills underlying reading acquisition—phonological awareness, speech-in-noise perception, rhythm perception, auditory working memory, and the ability to learn sound patterns—and show that each is linked to music experience. We link these five subskills through a unifying biological framework, positing that they share a reliance on auditory neural synchrony. After laying this theoretical groundwork for why musical training might be expected to enhance reading skills, we review the results of longitudinal studies providing evidence for a role for musical training in enhancing language abilities. Taken as a whole, these findings suggest that musical training can provide an effective developmental educational strategy for all children, including those with language learning impairments.

Keywords

music, reading, phonological, speech, brain, rhythm

Decades of research have established that musical training has profound effects on the development of the brain. Lifelong musicians show reliable differences in brain structure when compared to nonmusicians, including white matter organization within the corpus callosum (Lee et al., 2003; Schmithorst and Wilke, 2002; Steele et al., 2013) and the arcuate fasciculus (Bengtsson et al., 2005) and thicker gray matter in motor and auditory cortices (Bangert and Schlaug, 2006; Bermudez et al., 2009; Elmer et al., 2013; Gaser and Schlaug, 2003a,b; Hyde et al., 2009; Keenan et al., 2001; Schlaug, 2001; Schlaug et al.,

1995, 2005; Schneider et al., 2002, 2005; Sluming et al., 2002). Musical training's ability to alter the structure of the brain is an impressive demonstration that neural development is shaped by a complex interaction between genes and environment and can be, therefore, dramatically changed by experience throughout life.

That musical training shapes the brain is not in question. However, the limits of the influence of musical training are still being established. Are the benefits of musical experience limited to musical abilities, or do they extend to language abilities as well? Here, we review evidence that musical training can enhance language skills underlying reading ability. One of the ingredients necessary for transfer of learning from musical experience to language skills is overlap between the processes underlying the perception and production of language and music (Patel, 2010, 2011, 2013). The first section of this review, therefore, is structured around abilities and neural functions that have been shown to be vital for reading: phonological awareness, speech-in-noise perception, rhythm perception, auditory working memory, and sound pattern learning. All of these processes have also been shown to be enhanced by musical training. These links between musical and linguistic abilities, and evidence for an overlapping biological basis for performance in the two domains, demonstrate the close relationship between these two systems. Moreover, these findings suggest that musical training might provide an effective developmental educational strategy for all children, including those with language learning impairments. After laying this theoretical groundwork for why musical training might be expected to enhance reading skills, we review the results of longitudinal experimental studies providing evidence for a role for musical training in enhancing language abilities.

1 PHONOLOGICAL AWARENESS

Many language skills, from reading to speech perception and production, rely upon phonological awareness, the explicit knowledge of the components of speech and how they can be combined (Ramus, 2003; Ramus et al., 2003; Rvachew and Grawburg, 2006; Siegel, 2006). Phonological awareness, in turn, relies upon the ability to categorize speech sounds (Berent et al., 2012; Boets et al., 2008, 2011; King et al., 2002; Kraus et al., 1996; Reed, 1989; Richardson et al., 2003; Serniclaes et al., 2004; Sharma et al., 2006; Tsao et al., 2004; Vandermosten et al., 2011), which are distinguished by small differences in timing and frequency content. The syllable [da], for example, can be distinguished from [ta] by as little as 10 ms voice onset time. The auditory system's hallmark ability to represent timing and frequency with high degrees of precision is, therefore, vital to language acquisition and use, and children who display deficits in auditory temporal and frequency resolution also exhibit problems with language skills. For example, children with language learning impairments have difficulty detecting a sound when it is followed immediately by a noise burst, a phenomenon known as backward masking (Gibson et al., 2006; Griffiths et al., 2003; Marler et al., 2001, 2002; McArthur and Hogben, 2001; Montgomery et al., 2005; Tierney and Kraus, 2013a; Wright et al., 1997). These children do not perform poorly when the noise is presented simultaneously with the tone

(Montgomery et al., 2005), suggesting that the problem does not stem from a global auditory deficit but that language skills are specifically tied to the precision of temporal encoding in the auditory system. Further evidence for a link between reading ability and auditory temporal encoding comes from research showing that reading skill is linked to the ability to tap consistently to a beat and the ability to discriminate rhythmic patterns (reviewed below).

Not only is precise temporal encoding necessary for speech discrimination, but precise frequency representation is crucial as well, as many speech sounds can be differentiated on the basis of frequency content or changing frequency contours. Accordingly, the ability to detect sinusoidal changes in frequency is also linked to reading skills and phonological awareness (Boets et al., 2008, 2011; Gibson et al., 2006; Talcott et al., 2000; Wright and Conlon, 2009). Further evidence for a link between frequency and pitch perception and reading skill comes from studies of the ability to discriminate pitch patterns. For example, normal-reading subjects perform better than learning-disabled readers on tests of tonal pattern discrimination (Atterbury, 1983, 1985). Other researchers (Barwick et al., 1989) found that reading ability correlated with tonal memory and chord discrimination in a group of 9-year-olds. Lamb and Gregory (1993) found that pitch discrimination was significantly related to reading ability in 5-year-olds. Anvari et al. (2002) found that melody and chord discrimination correlated with phonemic awareness and reading. Forgeard et al. (2008) found that children with dyslexia showed deficits on melody discrimination.

Speech sounds are brief in natural speech. As a result, detecting and discriminating speech sounds not only requires precise representations of time and frequency information; the listener must also be able to make rapid auditory judgments, which may therefore be particularly important for the development of phonological awareness. Certain perceptual judgments are only difficult for children with language learning problems if they must be completed rapidly, in a brief amount of time (Tallal and Gaab, 2006); these skills include detection of the order of stimuli (Breier et al., 2003; Griffiths et al., 2003; Rey et al., 2002; Tallal, 1980; Tallal and Piercy, 1973a,b), detection of tone pairs (Choudhury et al., 2007), and speech sound discrimination (Tallal, 2004; Tallal and Piercy, 1974, 1975). Moreover, rapid auditory processing ability in infants and toddlers can predict the acquisition of language skills later in life (Benasich and Tallal, 2002). Consistent with this relationship between reading and temporal processing, there is also, as discussed in detail below, a strong relationship between reading and the perception of rhythm.

Reading ability, therefore, relates to temporal and frequency resolution, rapid auditory processing, and phonological awareness. *These four skills may in turn rely upon a common neural foundation—neural synchrony in the auditory system—which may be crucial for the acquisition of reading.* Supporting this Neural Synchrony Hypothesis, the electrophysiological responses to sound of children with language impairments differ from those of normally developing peers in a number of ways, all indicative of reduced neural synchrony on time scales ranging from microseconds to seconds. For example, both rapid subcortical and cortical neural responses to sound are delayed in language-impaired children (Banai et al., 2005, 2009; Basu et al., 2010;

Benasich et al., 2006; Billiet and Bellis, 2011; Hayes et al., 2003; Hornickel et al., 2009, 2011; King et al., 2002; Rocha-Muniz et al., 2012; Song et al., 2008). Language-impaired children also tend to have subcortical responses to speech sounds with diminished representations of the higher frequencies (300 Hz and above) critical for speech sound discrimination (Banai et al., 2009; Hornickel et al., 2011, 2012; Rocha-Muniz et al., 2012; Wible et al., 2004), indicating decreased phase-locking that may underlie diminished behavioral frequency tracking. Language-impaired children's diminished neural synchrony may hinder their ability to discriminate speech sounds, as children with poor phonological awareness have subcortical responses that distinguish to a lesser degree between different speech sounds (Hornickel et al., 2009, 2011). Reading ability is also linked to trial-by-trial consistency in the subcortical response to sound (Hornickel and Kraus, 2013). Similarly, trial-by-trial response consistency in the cortex is diminished in rats with allelic variations in a gene associated with dyslexia (Centanni et al., 2013).

Many of these same indices of auditory neural synchrony are enhanced by musical training. For example, musicians have faster neural responses (on the scale of tenths of milliseconds) to both musical and speech sounds (Musacchia et al., 2007, 2008; Parbery-Clark et al., 2009b, 2012a,b,c; Strait et al., 2009, 2012, 2013a,b). Musicians also show enhanced encoding of the same frequencies of speech stimuli (above 300 Hz) which are less robustly represented in language-impaired children. Furthermore, just like the neural responses of good readers, the neural responses of musicians better encode the differences between speech sounds. See Fig. 1 for an illustration of how neural differentiation of speech sounds is impaired in participants with poor phonological awareness and enhanced in musicians. The trial-by-trial consistency of the neural response to sound has also been linked to the ability to move to a beat (Tierney and Kraus, 2013b) and is enhanced in older musicians compared to nonmusicians (Parbery-Clark et al., 2012b). See Fig. 2 for an illustration of how trial-by-trial response consistency relates systematically to reading ability (Hornickel and Kraus, 2013) and is enhanced in musicians (Skoe and Kraus, 2013). Cortical responses have been shown to be enhanced in musicians as well (Schneider et al., 2002, 2005; Shahin et al., 2003, 2004; Tervaniemi et al., 2006, 2009).

2 SPEECH IN BACKGROUND NOISE

According to the Neural Synchrony Hypothesis, children who have difficulty acquiring language skills have impaired auditory neural synchrony. If so, this impairment is likely to be more severe when stimuli are presented in conditions that tax the auditory system's ability to robustly represent the characteristics of sound. In fact, children with language impairments have particular difficulty perceiving speech when it is presented in background noise (Boets et al., 2007, 2011; Bradlow and Kraus, 2003; Cunningham et al., 2001; Geiger et al., 2008; Sharma et al., 2006; Ziegler et al., 2009). Background noise disrupts the neural responses to sound in children with language impairment, with enlarged effects of noise including diminished

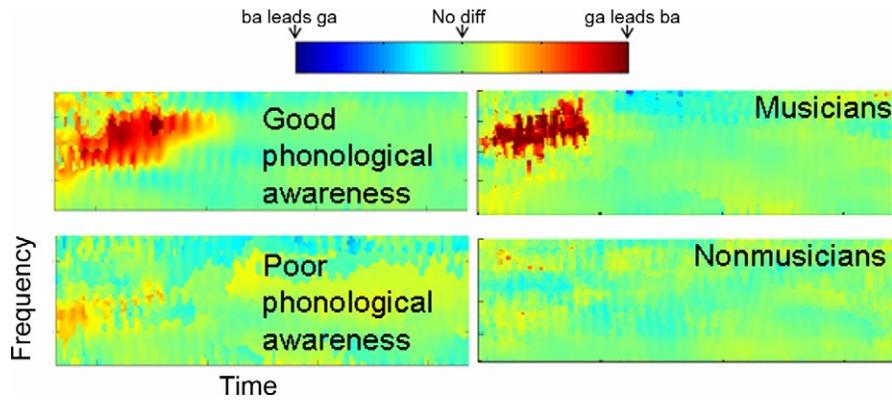


FIGURE 1

Neural differentiation of speech sounds underlies phonological awareness ability and is enhanced in musicians. Differences in high-frequency spectral content that acoustically differentiate consonants are converted to neural timing differences. These timing differences can be examined by analyzing phase shifts at particular frequencies between neural responses to different consonant–vowel syllables. (Left) Children with good phonological awareness as measured by the Comprehensive Test of Phonological Processing show larger phase shifts between responses to the speech syllables /ba/ and /ga/ (White-Schwoch and Kraus, submitted). (Right) In young adults, musicians (began practicing by age 7, at least 12 years of training) also show larger phase shifts between responses to /ba/ and /ga/ (replotted with permission from Parbery-Clark et al., 2012c). These phase shifts are limited to the response to the consonant–vowel transition, and are absent in the representation of the steady-state vowel, during which period the two syllables are identical.

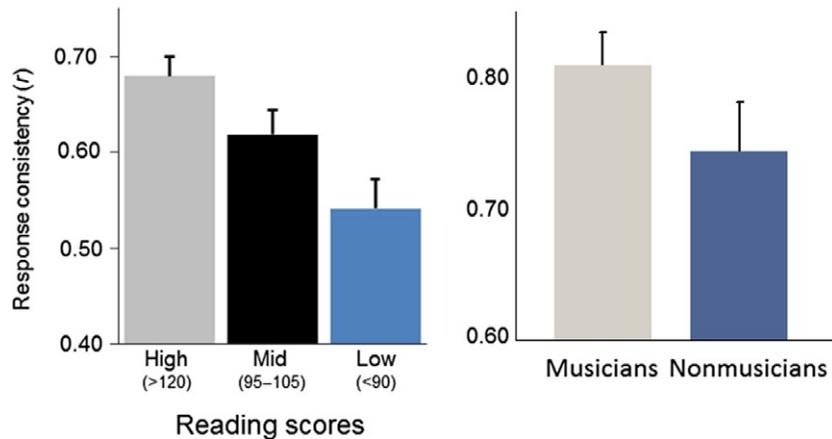


FIGURE 2

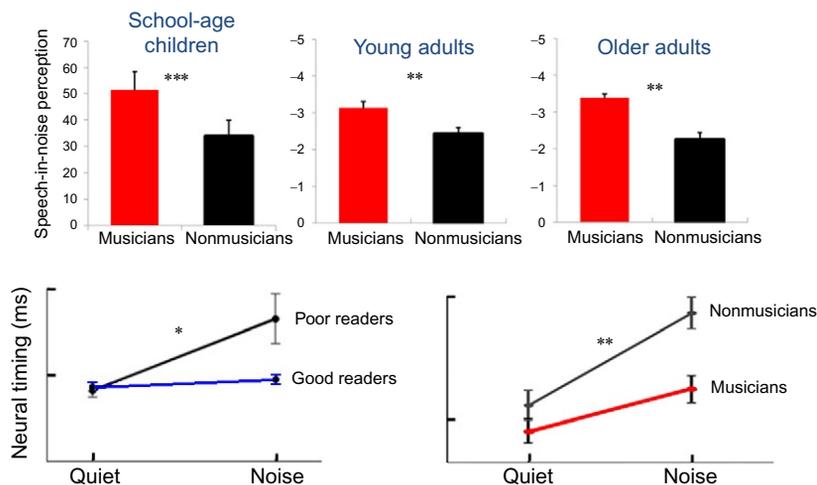
Trial-by-trial neural response consistency varies systematically with reading ability (left panel) (modified from Hornickel and Kraus, 2013) and is enhanced in musicians (right panel) (modified from Skoe and Kraus, 2013). Musicians were trained on a wide variety of instruments beginning by age 12. These data span a wide variety of ages, combined across several studies, and thus the number of years of training varied depending on the age of the population studied. Response consistency is measured by dividing all the neural responses to a sound collected in a given subject into two halves, averaging these trials to form two different waveforms, and then correlating the two waveforms.

correlations between the stimulus and the response, delayed responses, and smaller amplitudes (Anderson et al., 2010; Cunningham et al., 2001; Warrier et al., 2004; Wible et al., 2005).

Musical training, on the other hand, increases the auditory system's resilience to noise and other sources of signal degradation, decreasing the effects of background noise and reverberation on response amplitude, timing, and encoding of speech harmonics (Bidelman and Krishnan, 2010; Parbery-Clark et al., 2009b, 2012a; Strait et al., 2012, 2013b; Tierney et al., 2013 reviewed in Strait and Kraus, 2013). Musicians also are better able to perceive speech degraded by noise or reverberation across the life span, from infancy through old age (Bidelman and Krishnan, 2010; Parbery-Clark et al., 2009a, 2011a, 2012a; Zendel and Alain, 2012, 2013; Tierney et al., 2013; reviewed in Kraus et al., 2012). See Fig. 3 for a demonstration of the musician advantage for speech-in-noise perception, the excessive noise-induced delay in reading impaired children (Anderson et al., 2010), and the smaller noise-induced delay in the musician neural response to sound (Strait et al., 2012). See Table 1 for an overview of the neural "signatures" to speech syllables linked to both reading ability and musical experience (Kraus and Nicol, *in press*).

3 RHYTHM

Correctly perceiving the structure of music requires the perception and maintenance in memory of patterns in time extending over several seconds. Rhythmic structure in music does not consist solely of durational patterns, however; notes are also given different levels of prominence based on how they align with a metrical framework that operates on multiple levels (Palmer and Krumhansl, 1990). The presence of metric structure helps guide beat perception: When tapping to the beat of rhythmic patterns, participants tend to tap close to beats that fall at the beginning of a measure rather than in the middle (Patel et al., 2005). Similarly, when perceiving speech, the listener can take advantage of durational regularities such as the slowing that tends to occur as speakers approach the ends of sentences (Fant et al., 1991; Klatt and Cooper, 1975; Vaissière, 1991; Venditti and van Santen, 1998) and the somewhat predictable occurrence of syllables with different degrees of stress, one correlate of which is duration (Lieberman, 1960). These temporal regularities can be useful cues for speech segmentation (Cutler and Butterfield, 1992; Nakatani and Schaffer, 1978; Smith et al., 1989), which is necessary for the development of phonological awareness. Supporting the role of speech rhythm in the development of phonological awareness and reading ability, good readers show a greater sensitivity to speech rhythm as measured by tasks such as distinguishing between compound nouns and noun phrases (i.e., "lighthouse" vs. "light house") and matching a low-pass-filtered spoken phrase with one of two nonfiltered phrases (Gutiérrez-Palma and Palma Reyes, 2007; Holliman et al., 2010; Whalley and Hansen, 2006; Wood, 2006; Wood and Terrell, 1998).

**FIGURE 3**

Speech-in-noise perception is linked to both reading ability and musical training. (Top) Musicians benefit from enhanced speech-in-noise perception across the lifespan. Left, standardized scores; center and right, signal-to-noise threshold in dB (modified from [Kraus et al., 2012](#)). School-age children musicians ($n=15$) began training by age 5 and trained for at least 4 years (nonmusician, $n=16$); young adult musicians ($n=16$) began training by age 7 and trained for at least 10 years (nonmusician, $n=15$); older adult musicians ($n=18$) began training by age 9 and trained for at least 40 years (nonmusician, $n=19$). (Bottom left) Background noise has a less disruptive effect on the timing of the neural response to sound in good readers (blue) than poor readers (black) (participants divided into top vs. bottom halves based on performance on the Test of Word Reading Efficiency; modified from [Anderson et al., 2010](#)). (Bottom right) Background noise has less of a disruptive effect on the timing of the subcortical electrophysiological response to sound in children with musical experience (red) compared to children with no musical experience (black) (modified from [Strait et al., 2012](#)). (* $p<0.05$; ** $p<0.01$; *** $p<0.001$).

Tracking rhythmic patterns is, therefore, vital for both music and speech perception, which in turn is important for the acquisition of reading skills. Moreover, it has been suggested that the same neural mechanism is responsible for tracking rhythm in music and speech. An influential theory of musical rhythm perception, Dynamic Attending Theory, proposes a set of neural oscillators that phase-lock and resonate to the temporal structure of music, resulting in an attentional focus that waxes and wanes, following the rhythmic structure of a piece or song ([Large, 2000, 2008](#); [Large and Jones, 1999](#); [McAuley and Jones, 2003](#); [Velasco and Large, 2011](#)). As evidence in support of this theory, listeners are faster at performing a variety of perceptual tasks if stimuli are presented aligned with an expected beat ([Barnes and Jones, 2000](#); [Bolger et al., 2013](#); [Escoffier et al., 2010](#); [Grube and Griffiths, 2009](#);

Table 1 Musicians and good readers show enhancements in similar neural measures in response to speech syllables, suggesting overlapping biological bases for musical expertise and reading ability

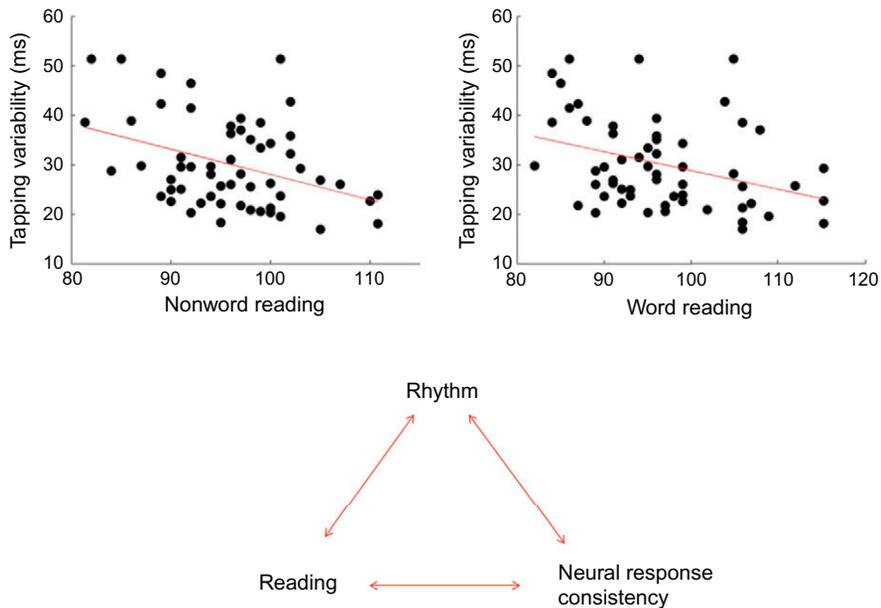
	F0 syllable representation	Speech formant representation	Onset timing	Syllable harmonics	Response consistency	Response disruption by background noise
Musicians	No relationship	Enhanced, earlier	Earlier	Enhanced	Enhanced	Lessened
Good readers	No relationship	Enhanced, earlier	Earlier	Enhanced	Enhanced	Lessened

In particular, reading acquisition may rely on neural synchrony, which musical training enhances.

Jones et al., 2002; Ladinig et al., 2009; Miller et al., 2013). Stimuli aligned with stronger metrical positions also give rise to larger electrophysiological potentials (Abecasis et al., 2005, 2009; Brochard et al., 2003; Geiser et al., 2009, 2010; Ladinig et al., 2009; Pablos Martin et al., 2007; Potter et al., 2009; Schaefer et al., 2011; Vlek et al., 2011; Winkler et al., 2009) and greater oscillatory activity in the beta and gamma range (Iversen et al., 2009; Snyder and Large, 2005). Moreover, neural oscillations have been recorded which reproduce the perceived rhythmic structure of abstract rhythmic patterns (Nozaradan et al., 2011, 2012).

A similar neural mechanism has been proposed for the tracking of the rise and fall of speech amplitude over time (Goswami, 2011; Poeppel et al., 2008): phase-locking of slow neural oscillations in the delta and theta range (2–7 Hz). This Temporal Sampling Hypothesis proposes that delta/theta oscillatory phase-locking selectively “samples” the low-frequency information in the amplitude envelope, which is crucial for the segmentation of speech and discrimination of speech sounds (Drullman, 1994). Supporting this hypothesis, electrophysiologic recordings from auditory cortex can reflect the speech envelope (Abrams et al., 2008; Aiken and Picton, 2008; Doelling et al., 2013), and the phase of slow oscillations in neural responses can be used to discriminate spoken sentences (Luo and Poeppel, 2007). That this envelope tracking is important for the development of language skills rather than a mere epiphenomenon is demonstrated by the fact that while good readers show right-lateralized envelope tracking, poor readers show envelope tracking that is distributed symmetrically across the two hemispheres (Abrams et al., 2009). Similarly, while normally developing subjects show right-lateralized phase-locking to low-frequency (2 Hz) amplitude modulation, subjects with dyslexia show symmetrically distributed phase-locking (Hämäläinen et al., 2012).

If the Dynamic Attending Theory and the Temporal Sampling Hypothesis are both correct, rhythm in music and the envelope of speech may be tracked biologically via the same mechanism—phase-locking of low-frequency neural oscillators to slow rises and falls of amplitude, a mechanism that (like the fine temporal and frequency representation discussed in the first section of this chapter) relies upon robust neural synchrony. Thus, strengthening this mechanism through training in one domain could lead to benefits for the other. This shared mechanism could explain why reading ability and phonological awareness relate to a variety of rhythm-tracking abilities, including discrimination of stimuli based on amplitude rise times (Goswami et al., 2002, 2011; Hämäläinen et al., 2005; Leong et al., 2011; Muneaux et al., 2004; Surányi et al., 2008; Thomson and Goswami, 2008; Thomson et al., 2006) and temporal patterns (Anvari et al., 2002; Atterbury, 1983, 1985; Douglas and Willatts, 1994; Forgeard et al., 2008; Huss et al., 2011; McGivern et al., 1991; Overy, 2000, 2003; Strait et al., 2011), reproduction of rhythmic patterns (Atterbury, 1983, 1985; Creak, 1936; Dellatolas et al., 2009; Peynircioglu et al., 2002; Rautenberg, 2013), tempo reproduction (Moritz et al., 2012), and tapping to the beat of music (David et al., 2007). Children with language learning impairment have been shown to tap more variably to a beat (Corriveau and Goswami, 2009; Thomson and Goswami, 2008; Thomson et al., 2006; Wolff, 2002), and this

**FIGURE 4**

The ability to tap to a beat is linked to reading ability and is strengthened with musical training (Slater et al., 2013). (Top) Good readers (according to score on the Woodcock-Johnson III standardized tests Word Attack and Letter-Word ID) tap less variably to the beat of a metronome (replotted with permission from Tierney and Kraus, 2013a). Word reading, $r = -0.38$, $p = 0.0036$; nonword reading, $r = -0.35$, $p = 0.0067$. (Bottom) The relationship between reading and rhythm may in part be driven by a shared reliance on precise auditory encoding, as both reading and beat synchronization ability relate to the consistency of the neural response to sound.

relationship between beat synchronization and reading ability holds in a typically developing population as well (Tierney and Kraus, 2013a). Musical training leads to increased rhythmic skills: for example, compared to nonmusicians, musicians produce less variable taps when drumming to a metronome (Krause et al., 2010a,b; Repp, 2010; Repp and Doggett, 2007), and a single year of music training in elementary school leads to an enhanced ability to keep a constant tempo when tapping out a beat (Slater et al., 2013). Given potential overlap between rhythm-tracking mechanisms in speech and music, rhythmic musical training may be particularly beneficial for enhancing reading acquisition. In fact, training in beat synchronization has indeed been shown to lead to improved reading fluency (Taub and Lazarus, 2012). See Fig. 4 for an illustration of how reading relates to rhythm skills such as beat synchronization (Tierney and Kraus, 2013a).

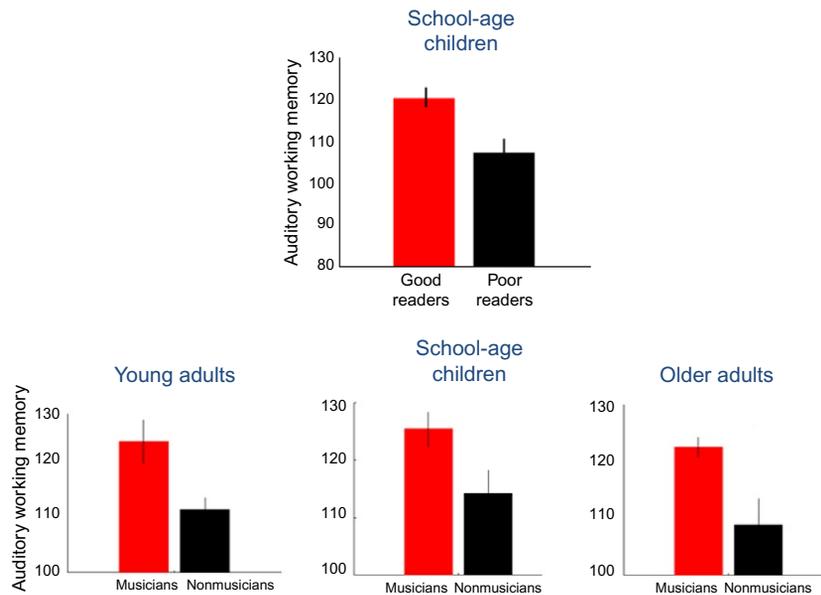
4 AUDITORY WORKING MEMORY

As described above, reading acquisition depends heavily upon auditory perceptual skills such as the ability to perceive and neurally represent differences in timing. Acquiring language and learning to read also depend on auditory working memory, however; conversing with a partner requires the ability to remember and act upon what was just said, and the development of phonological awareness relies upon the ability to keep an auditory sequence in mind long enough to decode it into its component sounds. Poor readers show low performance on verbal short-term memory tests including recall of word lists (Brady et al., 1983; Gathercole and Baddeley, 1990), letter lists (Siegel, 1994), and sequences of digits (Strait et al., 2010). Poor readers also have difficulty with verbal working memory tests such as backwards recall of digit sequences (Gathercole et al., 2006) and word list recall during simultaneous semantic comprehension (Brady et al., 1983; Gathercole et al., 2006).

In the course of learning to perform music, students must learn to memorize long auditory passages and sequences of movements, pick out and focus attention on a single sound out of a surrounding cacophony, and take in a complex auditory passage at a glance. In particular, auditory working memory is relevant to almost all musical tasks, from tuning an instrument to learning a passage by ear to improvising. Over time, experience with the challenges of music performance confers cognitive benefits: verbal short-term memory, for example, is enhanced in musicians (Chan et al., 1998; Ho et al., 2003; Jakobson et al., 2008; Tierney et al., 2008). Musicians also show superior performance on tests of auditory working memory (Parbery-Clark et al., 2009a, 2011a; Strait et al., 2013b; reviewed in Kraus et al., 2012). These results suggest that the same cognitive resources underlying auditory working memory, which is impaired in poor readers, may be enhanced by musical training. Figure 5 illustrates that both good readers and musicians perform better on tests of auditory working memory (Kraus et al., 2012).

5 LEARNING SOUND PATTERNS

To acquire the phonemic knowledge necessary for the acquisition of reading skills, it is not enough to be able to represent sound precisely, discriminate between sounds, and hold sequences of sounds in memory. To learn the locations of the boundaries between words and between syllables, budding readers must also be able to pick up on sound patterns and adjust their expectations accordingly—that is, they must be able to learn about sound. Typically developing children, when presented with a stream of speech syllables in which certain syllables tend to be followed by certain other syllables (i.e., /du/ always precedes /ta/), are able to extract the underlying transitional probabilities governing the formation of words (Saffran et al., 1996, 1999), and their ability to do so relates to their expressive vocabulary. Learning-impaired children, however, are less successful at detecting these regularities, showing performance no different from chance (Evans et al., 2009).

**FIGURE 5**

Auditory working memory is linked to both reading ability and musical training. (Top) School-age good readers (divided into halves based on performance on the Test of Silent Word Reading Fluency) perform better (standardized scores) than poor readers on the Woodcock-Johnson III test of auditory working memory (unpublished data). (Bottom) Musical experience is linked to an enhancement of auditory working memory across the lifespan.

Modified from Kraus et al. (2012).

Musicians, on the other hand, show an enhanced ability to lock onto regularities in sound. [Francois and Schön \(2011\)](#) demonstrated that musicians were better able to learn both musical and linguistic regularities in a sung language: the degree to which stimuli followed an underlying musical or linguistic rule modulated electrophysiological responses to a greater extent in musicians compared to nonmusicians. In a follow-up longitudinal study, [François et al. \(2013\)](#) studied 8-year-old children for 2 years as they were trained in either music or painting. At pretest, after 1 year, and after 2 years of training, the painting group was unable to learn the transitional probabilities between stimuli. The music group performed at chance at pretest, but performed above chance after 1 year and again after 2 years of training, demonstrating an enhanced ability to extract the rules underlying word segmentation. Furthermore, whether or not stimuli followed the learned rule modulated electrophysiological responses to a greater extent in the music group after 2 years of training. Similarly, [Skoe et al. \(2013\)](#) found that subjects with musical training were better able to detect the transitional probabilities within tone sequences and

the number of years of training correlated with the extent to which the presence of statistical patterns in tone sequences affected the subcortical response to sound.

Another, simpler way to examine the neural tracking of stimulus regularities is to present a speech sound in one of two contexts: either within a stream consisting of only that same sound or among a set of other sounds. In good readers, the sound presented in the consistent, predictable context elicits a larger electrophysiological response compared to the unpredictable condition. In poor readers, however, the response is more similar in the two conditions (Chandrasekaran et al., 2009; Strait et al., 2011), suggesting that reading is tied to the ability to track patterns in sound. This predictability enhancement is also tied to musical aptitude (Strait et al., 2011) and is larger in musicians than in nonmusicians (Parbery-Clark et al., 2011b). Musical training may, therefore, exercise mechanisms for the detection of patterns in sound that are also critical for reading acquisition.

6 SUMMARY AND LIMITATIONS OF CROSS-SECTIONAL STUDIES

The preceding sections have laid the theoretical groundwork for why one might expect musical training to enhance the ability to read. Although the processes involved in playing an instrument and connecting printed letters to speech sounds and meaning may at first seem quite different, when music and reading are broken down to their components there is quite a bit of overlap in the resources upon which the two abilities draw. Precise temporal and frequency representation, rapid auditory processing, perceiving a signal in noise, auditory working memory, and auditory pattern learning are all abilities called upon in the process of learning music and reading. Moreover, overlap has been reported in the biological foundations of reading and music: rhythmic patterns in both speech and music may be tracked by phase-locking of slow oscillations and precise neural synchrony may be vital for both the development of phonological awareness and rhythmic ability.

There is ample reason to believe, therefore, that musical training could have a positive impact on children learning to read. The previously discussed links between reading and music have, however, come largely from cross-sectional and correlational studies, indicating that proficient reading ability and musical training are linked to similar perceptual and neural mechanisms. These results suggest that musical training could improve reading ability, but cannot be taken as strong evidence for this claim. Certain other factors could conceivably account for relationships between musical and reading skills. Although the majority of these studies attempted to control for factors such as general intelligence and socioeconomic background, less tangible factors such as parental involvement in education may be playing a role as well and are more difficult to control for. Somewhat stronger evidence in support of a causative influence of musical training on language skills comes from correlations between extent of musical training and performance; a study by Corrigall and Trainor (2011), for example, reported positive correlations between length of music

training and reading comprehension performance, even after controlling for age, socioeconomic status, IQ, and number of hours that children spent reading per week. Length of music training has also been reported to correlate with speech-in-noise perception (Parbery-Clark et al., 2009a) and auditory working memory (Strait et al., 2012; reviewed in Skoe and Kraus, 2013). Nevertheless, it remains possible that participants with certain personality characteristics are more likely, *a priori*, to continue with musical training rather than stopping after a few years (Corrigan et al., 2013). Longitudinal experimental studies, therefore, provide the most ironclad evidence for a causative relationship between musical experience and reading ability. In the past few decades, there have been numerous attempts to design longitudinal experiments to investigate the question of how undergoing musical training affects linguistic ability, including the acquisition of reading and precursor skills such as phonological awareness. In this section, we review the literature on musical

Table 2 Summary of longitudinal studies of the effect of music training on reading ability and phonological awareness

Study	Subjects	Music training	Control group	Improvements relative to control group
Without random assignment				
Hurwitz et al. (1975)	20 7-year-olds	Experimenter-designed	No training	Reading
Standley (1997)	32 4–5-year-olds	Experimenter-designed	No training	Pre-reading skills
Overy (2000, 2003)	9 dyslexic 9-year-olds	Experimenter-designed	None	Phonological awareness and spelling
Register (2004)	86 5–7-year-olds	Experimenter-designed to teach language skills	Literacy-training television show	None
Gromko (2005)	103 5-year-olds	Experimenter-designed	No training	Phoneme segmentation fluency
Rauscher and Hinton (2011)	75 5-year-olds	Private Suzuki violin instruction	Swimming lessons or no training	Word naming and phonemic awareness
Moritz et al. (2012)	30 5-year-olds	Preexisting school music classes	Less frequent music classes	Phonological awareness
Tierney et al. (2013)	43 adolescents	Preexisting school music classes	Fitness training	Earlier neural timing

With random assignment				
Roskam (1979)	36 learning-disabled 6–9-year-olds	Experimenter-designed	Learning disability rehabilitation	None
Douglas and Willatts (1994)	12 reading-disabled 9-year-olds	Experimenter-designed	No training	Reading
Fisher (2001)	80 5-year-olds	Experimenter-designed to teach language skills	Language skill teaching without music	Phoneme segmentation and oral skills
Costa-Giomi (2004)	80 fourth-graders	Private piano instruction	No training	None
Register et al. (2007)	33 second-graders, 6 reading-disabled	Experimenter-designed to teach reading skills	No training	Word knowledge
Forgeard et al. (2008)	44 6-year-olds	Unclear	No training	Word reading
Moreno et al. (2009)	32 8-year-olds	Computer-based	Painting or no training	Reading
Degé and Schwarzer (2011)	41 5–6-year-olds	Experimenter-designed	Phonological skill training	Phonological awareness
Herrera et al. (2010)	97 4-year-olds	Experimenter-designed to teach phonological skills	Phonological skill training or no training	Phonological awareness
Taub and Lazarus (2012)	280 students, age unclear	Synchronization to metronome	No training	Reading
Bhide et al. (2013)	19 poor readers, 6–7 years old	Computer-based rhythm training	Reading intervention	None
Cogo-Moreira et al. (2013)	240 poor readers, 9 years old	Experimenter-designed	No training	Reading and phonological awareness
Rautenberg (2013)	159 7-year-olds	Experimenter-designed	Visual arts training or no training	Word reading
Slater et al. (2013)	42 6–9-year-olds	Previously existing music program	No training	Reading

training and reading. See [Table 2](#) for a summary of the experimental design and results of these studies.

7 LONGITUDINAL MUSIC TRAINING STUDIES

The gold standard experimental model for learning/training studies is random assignment to an experimental group with two control groups: an active control and a passive control, with a unified course of training. If children are not randomly assigned to either a musical training group or a control group, the possibility remains that any differences which emerge between the two groups are due to some preexisting difference in motivation or ability which caused some of the children to pursue music in the first place. Not using an active control group leaves open the possibility that trained children are improving relative to control children simply due to the extra attention they are receiving from instructors. And ideally, assessments will also be made before training, just after training, and long after training has stopped, to determine whether any training-related benefits are retained after training ceases.

In practice, few if any fully controlled studies of musical training can hew to these stringent criteria because of challenges inherent in assessment of training in a real-world setting. It can, for example, be very difficult to conduct a study on the effects of musical training with random assignment, as subjects who are interested in musical training may be unwilling to postpone the start of their training until after the completion of the study. Furthermore, finding an active control training regimen that matches musical training in intensity and motivation can be logistically difficult. Finally, if children are engaged in musical training as part of a music class or other structured program that briefly brings these children together, it can be quite difficult to continue to track them for months after instruction ceases. There is often, therefore, a tradeoff between the ecological validity of the musical instruction presented to subjects and the extent to which study designs can meet these criteria. On the one hand, using training programs or lesson plans developed by the experimenter can enable more rigorously controlled studies, but the results of such studies will be somewhat difficult to generalize to the effects of real world music learning conditions. On the other hand, by studying existing programs that have been demonstratively successful in teaching children musical skills, researchers can maximize the applicability of their research to educators, at the cost of certain limitations in study design. The body of knowledge about the effects of musical training on reading ability has been contributed to by a broad variety of study designs which, as a whole, support the notion that musical training can enhance reading acquisition.

To date, studies on the effects of musical training on language skills and the neural encoding of sound have used a variety of behavioral and neural assessments. This approach has revealed a variety of advantages linked to musical training, but comparisons among studies have been difficult, as difference in outcomes could be either due to differences in the extent, type, or age of onset of training or due to differences in the outcome measures themselves. The use of a uniform biological assessment of

the neural encoding of sound—that is, using the same measure irrespective of age or species—would enable cross-study comparison, allowing researchers to determine how musical training affects different populations or how the effects of different kinds of musical training vary. We have pioneered the use of a neural, scalp-electrode recorded measure with several unique attributes, the complex auditory brainstem response (cABR). This electrophysiological response closely mirrors the acoustic characteristics of the evoking stimulus (Skoe and Kraus, 2010), and can be modified by experience (Kraus and Chandrasekaran, 2010). Moreover, while the cABR shows a high degree of test–retest reliability (Hornickel et al., 2012; Krishnan et al., 2012), there are large individual differences in aspects of the cABR between participants which have been linked to a variety of communication skills, including speech-in-noise perception and reading (Anderson et al., 2010). Understanding the source of these individual differences and how they underlie differences in communication skills is an important direction for future neuroeducational work. This neural response represents a snapshot into a neural hub of hearing—depicting a cohesive sensory-cognitive-reward system. More widespread adoption of this measure would, therefore, both enable researchers to study the effects of music on the biological basis of speech perception and language skills and facilitate the synthesis of music training research into an integrated whole. To facilitate the cABR’s adoption as a widely used measure across studies future work should focus on the improvement of the efficiency and ease-of-use of the collection of this biological metric.

8 EXPERIMENTAL STUDIES WITHOUT RANDOM ASSIGNMENT

In the first longitudinal study ever conducted on the question of whether musical training enhances reading ability, Hurwitz et al. (1975) gave children from one school system musical training from the Kodaly curriculum, a standard music education approach in use since the mid-twentieth century; children from a second school system were given no special training. The two groups were matched on reading ability at pretest, but after 1 and 2 years of training the experimental group had better reading scores than the control group. Standley (1997) gave prekindergarten children either musical training designed by the experimenter or no training, and found that the music training group, compared to the control group, showed gains in performance on tests of language knowledge necessary for reading acquisition. However, the musical training included focus on pre-reading and writing skills, and thus it is difficult to know whether the experimental group’s gains can be attributed to the musical aspects of the training *per se*. Overy (2000, 2003) gave rhythm-based musical training designed by the experimenter to a group of children and found gains in phonological awareness and spelling; given the lack of a control group, however, these results are difficult to interpret. Register (2004) taught early literacy skills to children via either a television show or a musical curriculum designed by the researcher and administered by a music therapist and found that the two approaches led to equivalent gains in preliteracy skills. Gromko (2005) gave music instruction

designed by the experimenter to children at a treatment school, while children at a control school were given no special training; children at the treatment school, but not control children, showed gains in phoneme segmentation fluency. [Rauscher and Hinton \(2011\)](#) gave 5-year-old children private, one-on-one Suzuki violin instruction, swimming lessons, or no training. The three groups did not differ at pretest, but at posttest, the violin group's performance on Letter-Word Calling and Phonemic Awareness tests had improved relative to the other two groups. [Moritz et al. \(2012\)](#) compared kindergartners from two different charter schools, one of which provided daily music lessons, and another which provided only one music lesson per week. Children from the school with more frequent music lessons showed greater gains in phonological awareness than children who were exposed to less musical training. Finally, longitudinal work in progress in our laboratory is examining reading ability over time in adolescents in charter schools who have elected to participate in either in-school music classes, ROTC training, or no special training. The musical training being studied has been used successfully for years at these schools to teach children musical skills. Preliminary data suggest that neural responses to a speech sound presented in noise are becoming less delayed in the musically trained group compared to the other two groups, supporting previous findings of a link between musical training and a lessening of the noise-induced delay in neural responses to sound ([Tierney et al., 2013](#)).

9 EXPERIMENTAL STUDIES WITH RANDOM ASSIGNMENT

Taken as a whole, the results reported in the previous section suggest that musical training in childhood may lead to increased phonological awareness and reading ability. However, without the use of random assignment, one cannot entirely reject the possibility that any gains made in the experimental group versus the control group are due either to a preexisting difference in personality ([Corrigall et al., 2013](#)), motivation, or ability (driving the experimental group to take up music lessons in the first place) or to preexisting differences in the classes or schools to which the two groups of subjects belonged. The strongest evidence for an effect of musical training on reading ability comes from experimental studies that have randomly assigned subjects to either a musical training group or a control group.

In the first study of musical training and reading to use random assignment, [Roskam \(1979\)](#) divided learning-disabled 6-9-year-old children into a control and two experimental groups, one of which was rehabilitated using standard techniques and the other of which received music therapy designed by the experimenter. No significant effects of training were found. In a small pilot study, [Douglas and Willatts \(1994\)](#) studied 12 reading-disabled children, half of which were given musical training designed by the experimenters. Reading scores for the musical training group increased from pretest to posttest, while scores for the control group did not change. [Fisher \(2001\)](#) compared children in kindergarten who learned language skills through lessons which incorporated music, compared to children who took more

traditional nonmusical classes. The music group showed greater gains in phoneme segmentation ability and oral skills. [Costa-Giomi \(2004\)](#) randomly assigned children to either a training group who received private, one-on-one piano instruction designed by individual piano teachers for 3 years or a control group that received no instruction and found no effects on academic achievement in either language or math. [Register et al. \(2007\)](#) compared second-grade students engaged in a music curriculum designed by the experimenters to students receiving no musical training and found that the music group experienced greater gains pre- to posttest in word knowledge. However, given that the music curriculum included instruction in reading strategies it is difficult to know whether the increased reading skill was driven by the musical aspects of the training. In a pilot study, [Forgeard et al. \(2008\)](#) found that six children given musical training improved more than children who received no training on word reading. (The exact nature of the musical training—in particular, whether it was classroom training or a program designed by the experimenter—is difficult to determine from the manuscript.)

Early work on musical training and reading skill using random assignment, therefore, did not provide strong evidence for the effectiveness of musical training; the studies cited above all either reported null results, used extremely small numbers of subjects, or presented musical training which included linguistic training. However, more recent work has used larger subject populations and reported much more promising results. [Moreno et al. \(2009\)](#), for example, gave children computer-based training designed by the experimenter to enhance either painting skills or musical skills. Only the children in the music group showed improvement in a reading task after training. [Herrera et al. \(2010\)](#) examined the development of phonological abilities in children in a control group, a group receiving phonological training, and a group receiving phonological training featuring additional musical elements. The training programs were designed by the authors. At posttest, the musical training group outperformed the other two groups on phonological awareness. [Degé and Schwarzer \(2011\)](#) compared the effects of a music program and a phonological skills program (both created by the authors) in preschoolers and found that the two training groups led to similar gains in phonological awareness. [Taub and Lazarus \(2013\)](#) gave children either training in synchronizing movements to a metronome or no training and found at posttest that the experimental group's reading scores were higher than the control groups' scores. [Bhide et al. \(2013\)](#) gave a group of 6–7-year-old children either a computer-assisted reading intervention or rhythm training designed by the experimenters including both musical and linguistic elements; both groups improved in reading ability by similar amounts. However, given that the rhythm training contained both musical and linguistic elements, it is difficult to determine whether the gains shown by the children in the rhythm group could be elicited by the musical elements alone. [Cogo-Moreira et al. \(2013\)](#), in a large-scale clinical study, found that musical training designed by the experimenters (compared to no training) led to increases in reading ability and phonological awareness in young poor readers when compliance was taken into account. [Rautenberg \(2013\)](#) found that music classes designed by the experimenter led to an improvement in word reading compared

to either visual arts classes or no classes. Finally, a longitudinal study from our research group is currently examining the development of reading skills over time in two groups of children, one of whom was assigned musical training as part of the Harmony Project, a nonprofit organization which for years has provided musical training to underserved children in gang-reduction zones of Los Angeles. All participants requested to participate in the Project; these participants were pseudo-randomly assigned to two groups. In the first year of the study, one group received musical training while a matched control group did not. The control group began music classes the following year. Preliminary results suggest that musical training led to increases in reading ability, speech in noise, and rhythm skills (Slater et al., 2013).

10 WHY MUSIC?

In summary, there is a theoretical basis for a link between musical training and reading ability, as the neural and cognitive resources necessary for reading acquisition and those resources drawn upon in the course of learning to play music overlap. Moreover, extensive empirical evidence collected over several decades indicates that musical training can enhance reading ability. Noteworthy is that some of the same aspects of neural encoding of speech that are deficient in individuals with communication difficulties such as dyslexia, reflecting decreased neural synchrony, are strengthened in musicians compared to their nonmusician peers, suggesting overlapping biological bases for musical expertise and reading ability (Kraus and Chandrasekaran, 2010; Strait and Kraus, 2011). These results may indicate that musical training can lead to increased neural synchrony throughout the auditory system, suggesting that music could be an effective way to boost reading skills in children. Nevertheless, the question remains: why not simply train reading itself? Would that not be a more direct, and potentially more effective, way of enhancing reading ability? Certainly, we do not mean to suggest that musical training should supplant reading training. Instead, we would argue for the inclusion of musical training as a part of a balanced school curriculum, including reading, foreign language instruction, mathematics, science, athletics, etc. Difficulties with reading can stem from a variety of sources. Some children are likely to draw the greatest benefit from musical training, while other children may respond better to other forms of instruction.

One of the reasons musical training can be such a powerful educational tool is that music is inherently rewarding, emotion-inducing, and attention-grabbing (Menon and Levitin, 2005; Patel, 2011, 2013). Neural plasticity can be enhanced by attention (Fritz et al., 2013) and motivation (David et al., 2012; Rutkowski and Weinberger, 2005), and neural plasticity can enhance perceptual learning (Reed et al., 2011). The rewarding nature of music listening and music performance (Salimpoor et al., 2013) makes it ideal for getting children interested in school and giving them the auditory, motor, and cognitive skills they need to learn to read and succeed, both in school and later in life. In fact, active training in early life can lead to benefits in task

performance in adulthood (Sarro and Sanes, 2011), but passive exposure to stimuli in juveniles does not have long-term benefits (Engineer et al., 2004; Sarro and Sanes, 2011). As music is one of the most active, absorbing ways that children can interact with sound, even a few years of music instruction early in life can have profound effects on the functioning of the nervous system years later (Skoe and Kraus, 2012; White-Schwoch et al., 2013). And of course, even if a given child receives no extramusical benefit from his or her instruction, at worst they will have gained an aesthetic appreciation with the potential to last a lifetime.

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